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Impact of precipitation changes on runoff and soil erosion in Korea using CLIGEN and WEPP

M.-K. Kim, D.C. Flanagan, J.R. Frankenberger, and C.R. Meyer

Abstract: The quality of spatially and temporally distributed weather information is critical in soil erosion model results because of the primary influence of rainfall on runoff and soil movement. Detailed climate data for the Water Erosion Prediction Project (WEPP) model can be generated by a climate generator (CLIGEN) based on long-term statistical parameters for more than 4,000 locations in the United States. The objectives of this study were to apply CLIGEN and WEPP and examine the effects of changing storm frequency, storm depth, or a combination of the two on predicted rainfall, runoff, and soil loss. Two different sites, Chun-Cheon and Jeon-Ju, were studied and compared for the period 1966 to 2005. Chun-Cheon is located at a higher altitude and is surrounded with forest, while Jeon-Ju is located in the plains. CLIGEN was used to generate 100-year climate sequences with daily climate data e.g., temperature, precipitation, wind, and solar radiation for a representative climate station in the study sites to predict runoff and soil loss with WEPP. Three precipitation change scenarios were examined in this study: (1) adjusting the number of days with rainfall, (2) adjusting the mean amount of rainfall on a wet day, and (3) a combination of 1 and 2. Observed mean annual precipitation at Chun-Cheon (1,305 mm [50.9 in]) was similar to Jeon-Ju (1,291 mm [50.4 in]). CLIGEN simulated mean annual precipitation depths in Chun-Cheon and Jeon-Ju were very close to the observed data. The WEPP model predicted runoff in Jeon-Ju was 48.8% higher than that in Chun-Cheon and estimated soil loss in Chun-Cheon was 55.6% higher than that in Jeon-Ju. Precipitation change scenario 3 that combined changes in precipitation occurrence with changes in rainfall storm depths showed the largest impacts on predicted runoff and soil loss. A combined 20% increase in these precipitation parameters resulted in increases of 44%, 54%, and 52% in generated average annual precipitation, predicted runoff and predicted soil loss, respectively, at Chun-Cheon, while increases at Jeon-Ju were 44%, 60%, and 27%. Increases in rainfall due to future climate change may thus potentially result in substantial and nonlinear increases in runoff and soil loss in Korea.

Key words: climate change—Korea—runoff—soil erosion—WEPP

The quality of spatially and temporally distributed weather information is critical in soil erosion model results because of the primary influence of rainfall intensity on runoff and initiation of soil movement. Recently, many atmospheric scientists have reported that climate change is occurring, both in terms of precipitation and temperature (Karl and Knight 1998; Groisman et al. 2001; Intergovernmental Panel on Climate Change Working Group I 2001; National Assessment Synthesis Team 2001). Climate change can affect agricultural production and soil and water conservation (O'Neal et al. 2005).

In general, increasing precipitation affects runoff and soil erosion directly, while temperature change affects soil erosion indirectly

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in several ways such as crop growth, crop production, irrigation, and so on (Stockle et al. 1992; Pruski and Nearing 2002b). Also, climate changes are likely to be accompanied by changes in crop management, as farmers adapt their management practices to the new climate (Schulze 2000; Leek and Olsen 2000; West and Wali 2002; Gao et al. 2002). The Soil and Water Conservation Society (2003) found that the research pointed to increasing soil erosion and runoff in the future by summarizing over 30 climate and soil erosion related studies for the United States. They determined that the potential impacts were serious enough to warrant increased attention by conservationists on changing policies to prepare for the anticipated impacts of more severe erosion and runoff on soil and water resources.

On a global scale, General Circulation Models (GCMs) have been developed by climate scientists over the past 50 years to evaluate shifts in climate due to atmospheric changes in carbon dioxide and other gases and subsequent increases in temperatures and fluid fluxes. The three initial groups in the 1960s were the Geophysical Fluid Dynamics Laboratory, the UCLA Department of Meteorology, and the National Center for Atmospheric Research, all in the United States. There are currently about 14 research groups with GCM development efforts (American Institute of Physics 2008). Because the GCMs work at a very coarse scale (>2° for both latitude and longitude), it is necessary to downscale information from a GCM to a finer scale that is more relevant for hydrologic and sediment process research.

Researchers examining spatial and temporal downscaling of results from GCMs for utilization in studies of the possible impact of climate change on natural resources, include Zhang (2005), Tripathi et al. (2006), Zhang (2007), and Ghosh and Mujumdar (2008). In particular, Zhang (2005, 2007) has developed a methodology for temporally and spatially downscaling from the coarse GCM output to much finer weather information necessary for simulating runoff and soil erosion that requires accurate predictions of daily occurrences of rainfall and temperatures. His approach derives univariate transfer functions obtained through calibration of probability distributions from GCM-projected results with observed weather station records and then assumes that the transfer functions for past climate will remain valid for future projections. Climate generator input parameters adjusted by Zhang (2005, 2007) included monthly values for mean daily precipitation depth on a wet day, variance of precipitation depth, conditional probabilities of a wet day following a wet day and a wet day following a dry day, mean maximum temperature, mean minimum temperature, and the standard deviations of the maximum and minimum temperatures. Other recent downscaling approaches include use of support vector machines (Tripathi et al. 2006) and relevance vector machines (Ghosh and Mujumdar 2008).

Soil erosion prediction models such as the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing 1995) can be used to assess the likely impact on runoff, soil loss, and biomass production for given climate change scenarios. The WEPP model has been a good predictor of soil erosion and water runoff at time scales ranging from individual events to long-term average annual (Laflen et al. 2004; Flanagan and Nearing 1995). The WEPP model is a process-based and continuous daily simulator to estimate sheet and rill erosion by water. Daily, monthly and yearly outputs are available over the entire simulation period. Furthermore, both temporal and spatial soil detachment and/or deposition can be predicted (Flanagan and Nearing 1995).

Detailed climate data for WEPP can be generated by a climate generator (CLIGEN) (Nicks et al. 1995) based on long-term statistical parameters for more than 4,000 locations in the United States. Typically CLIGEN and WEPP are run based on the current climate conditions. Some of the CLIGEN parameters are then perturbed to simulate future possible scenarios (Pruski and Nearing 2002a, 2002b; Zhang 2005, 2007; Zhang and Nearing 2005). Alternatively, observed or simulated rainfall or temperature values can be adjusted directly to generate different climate series (Favis-Mortlock and Savabi 1996; Favis-Mortlock and Guerra 1999). The difference in terms of predicted soil erosion can be interpreted to represent the likely impact of climate change on soil erosion.

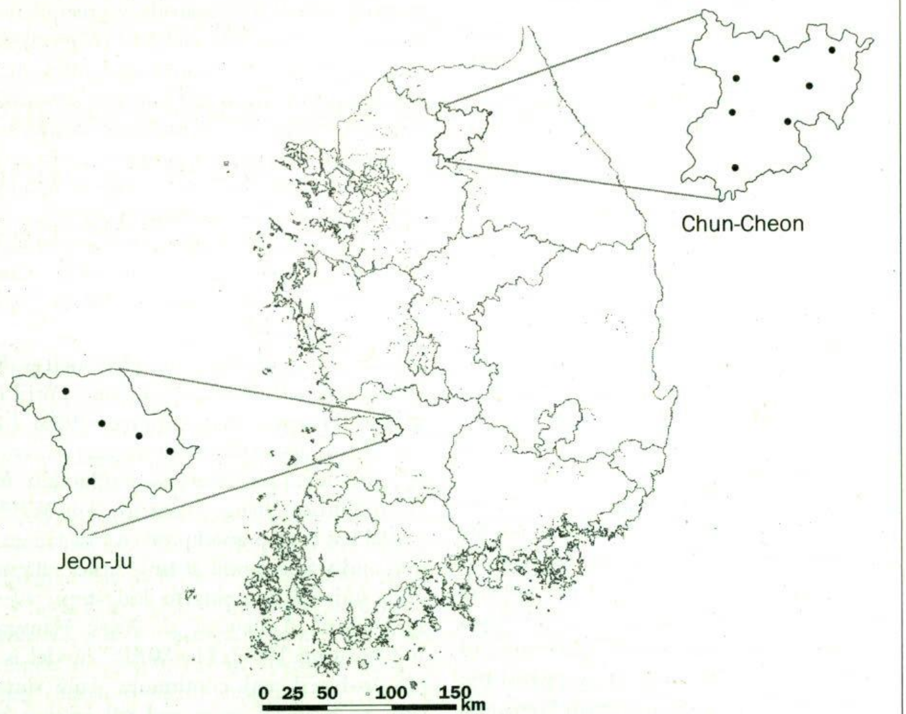
Pruski and Nearing (2002a) determined soil loss and runoff rates for the 21st century for eight locations in the United States using the HadCM3 model predictions coupled with the Water Erosion Prediction Project-Carbon Dioxide model (Nearing et al. 1989; Favis-Mortlock and Savabi 1996; Flanagan and Nearing 1995). Their results indicated that in every case where precipitation was predicted to increase significantly, erosion increased significantly. In the locations where decreases in precipitation were predicted, erosion decreased in some cases and increased in others. Zhang (2005) and Zhang and Nearing (2005) also used CLIGEN and the Water Erosion Prediction Project-Carbon Dioxide model to evaluate potential changes in runoff, soil erosion, and crop productivity at two different locations in Oklahoma. Generally runoff was predicted to decrease under all climate change scenarios, but runoff and soil erosion either remained the same or increased due to increased variability in rain storms and higher rainfall intensities.

Besides the United States, there are several international reports investigating soil erosion under climate change. Favis-Mortlock and Boardman (1995) found a 7% increase in precipitation could lead to a 26% increase in erosion in the United Kingdom using the Erosion Productivity Impact Calculator model (Williams and Sharpley 1989). Panagouloa and Dimou (1997) predicted increases in both the length and frequency of flood episodes (double and triple average streamflow) in Greece, based on precipitation outputs from the Goddard Institute for Space Studies climate change model, which they linked to possible increased bed and bank erosion. Schulze (2000), using the Crop Environment Resource Synthesis-Maize and Agricultural Catchments Research Unit models, predicted a 10% increase in precipitation would lead to a 20% to 40% increase in runoff in South Africa. With continuous soybeans in Brazil, Favis-Mortlock and Guerra (1999) predicted a −9% to +55% change in sediment yield for the year 2050 from three climate models, with the Hadley Centre climate model showing a 22% to 33% increase in mean annual sediment yield with a 2% increase in annual precipitation, and monthly sediment yield increasing by up to 103%. Zhang (2007) examined the effects of projected climate change in the Loess Plateau of China from 2010 to 2039. Predicted precipitation increased from 4% to 18% under three scenarios, while predicted runoff increased from 6% to 112% and predicted soil loss increased from −10% to +167%. The slope gradient used as well as the type of spatial downscaling (implicit or explicit) greatly influenced the results, as well as the increase in predicted CO_2 concentration and associated precipitation/temperature variation.

In theory, the CLIGEN parameters can be altered to simulate precipitation and/or temperature change scenarios. However, little is known about applying the WEPP model to different agricultural conditions in Korea and how climate change scenarios should be realistically represented there. Therefore, in this initial study, some of the major driving factors impacting runoff and soil loss were examined for two locations in Korea at which long-term climate data were available. The objectives of this study were to apply CLIGEN and WEPP and examine the effects of changing storm frequency, storm depth, or a combination of the two on predicted rainfall, runoff, and soil loss. Results from the modeling exercises could then be used to infer the applicability of WEPP in Korea and also to provide an initial assessment of how sensitive current land management practices may be to increasing precipitation from future climate change.

Figure 1

A map showing the location of studied sites, Chun-Cheon and Jeon-Ju, in the Republic of Korea. The blowup figures on left and right sides show the 5 and 7 representative hillslope profiles in Jeon-Ju and Chun-Cheon, respectively.



Materials and Methods

Study Site Description. Chun-Cheon is located in the north central part of the Republic of Korea (37°54' N, 127°44' E) covering an agricultural area of 124.7 km^2 (48.1 mi^2), and Jeon-Ju has an agricultural area of 50.0 km^2 (19.3 mi^2) and is located in southwestern Korea (35°49' N, 127°09' E) (figure 1). Yearly average temperatures in Chun-Cheon and Jeon-Ju are 10.6°C and 13.8°C (51.1°F and 56.8°F), respectively. The topography of both sites varies from steep forests to nearly level plains. Chun-Cheon is at a higher altitude (76.8 m [251.9 ft], base mean sea level) and has more forests than Jeon-Ju (53.5 m [175.5 ft], base MSL). For its agricultural land, Chun-Cheon consists of 33.6% paddy fields and 57.2% uplands, while Jeon-Ju has 32.9% paddy fields and 11.6% uplands. The soil at Chun-Cheon is a sandy loam with an average of 5.5% clay and 1.6% organic matter. At Jeon-Ju, the soil is a silty loam with 17.5% clay and 1.4% organic matter (table 1).

Implementation of WEPP Model. The Hillslope version (v2006.5) of the WEPP model (Flanagan and Nearing 1995) with its Windows-based Graphical User Interface was used in this study. In order to run the model, it was necessary to prepare four different input files for climate, soil, slope, and crop management. Soil, slope, and crop management inputs were developed utilizing information from the National Institute of Agricultural Science and Technology (NIAST) of Rural Development Administration in Korea. The Meteorological Information Web Service System-Disaster Prevention of the Meteorological Administration was able to provide the needed daily information (1966 to 2005) such as precipitation, temperature, solar radiation, and wind data required to drive the hydrology and plant growth components of the WEPP model. Site-specific crops and soil types were major components to select the representative hillslopes for each site, and topographic maps of each site were used to provide necessary information.

For Chun-Cheon, seven different hillslope profiles were identified, with uniform slope gradients ranging from 4.5% to 22.5%, and slope lengths ranging from 30 to 60 m (98.4 to 196.8 ft). At Jeon-Ju, five hillslope profiles

Table 1

Properties of the top 20-cm soil layer and estimated baseline values for effective hydraulic conductivity (K_b), interrill-(K_i) and rill-(K_r) erodibilities, and critical shear stress(τ_c) at the two study sites.

Location	Clay (%)	Sand (%)	OM (%)	CEC (cmol kg^{-1})	K_b (mm h^{-1})	K_i (kg s m^{-4})	K_r (s m^{-1})	τ_c (N m^{-2})	Albedo
Chun-Cheon	5.5	74.8	1.6	6.3	22.92	9.91×10^6	0.0151	0.8583	0.31
Jeon-Ju	17.5	8.7	1.4	10.0	2.20	1.641×10^6	0.0109	3.5	0.34

Notes: OM = organic matter. CEC = cation exchange capacity.

Table 2
Description of the soil types and crop management used for erosion modeling in the study sites, Chun-Cheon and Jeon-Ju.

Location	Number of hillslope	Soil series	Profile slope length (m)	Profile slope gradient (%)	Crop management
Chun-Cheon	1	Suam	60	11.0	Corn, conservation tillage
	2	Suam	30	11.0	Corn, conservation tillage
	3	Suam	40	4.5	Corn, conservation tillage
	4	Suam	40	11.0	Corn, conservation tillage
	5	Suam	60	11.0	Corn, conservation tillage
	6	Suam	40	22.5	Corn, conservation tillage
	7	Suam	60	4.5	Corn, conservation tillage
Jeon-Ju	1	Ihyeon	60	1.0	Soybean, conservation tillage
	2	Ihyeon	30	1.0	Soybean, conservation tillage
	3	Ihyeon	40	1.0	Soybean, conservation tillage
	4	Ihyeon	40	1.0	Soybean, conservation tillage
	5	Ihyeon	30	1.0	Soybean, conservation tillage

were delineated, all having 1.0% uniform slope gradients, and slope lengths from 30 to 60 m (98.4 to 196.8 ft) (table 2).

With these data, the WEPP model was run in a continuous mode for 100 years on each of the representative hillslopes (seven and five) at the two study sites, providing a total of 12 values for long-term predicted average annual runoff and soil loss. Arithmetic mean values at each site were then computed.

Soil, Slope, and Management Database Development. The NIAST of Korea was the source of publicly available soil, slope, and cropping management input data required for this study (table 2).

With regard to the soil inputs shown in table 1, percentages of sand and clay were obtained from the Agricultural Soil Information System of NIAST. Organic matter and cation exchange capacity were also obtained from Agricultural Soil Information System. Effective hydraulic conductivity (K_e) was computed internally by the WEPP model on the basis of sand and clay contents and cation exchange capacity. The interrill erodibility (K_i), the rill erodibility (K_r), and the critical hydraulic shear stress (τ_c) were computed as suggested in the WEPP User Summary (Flanagan and Livingston 1995). Initial soil profile saturation was set to 75% for all soil files. The soil albedo was estimated with the Baumer equation (Flanagan and Livingston 1995).

The WEPP slope input files for each representative hillslope profile at each study site were created based on the slope and slope length given in the detailed soil map (1:25,000) from NIAST. A uniform shaped slope for all hillslopes was assumed.

For the cropping management files, some existing input files for corn and soybeans were used, but it was necessary to edit the parameters such as planting, harvesting, tillage, and so on. In particular, adjusted crop parameters were based on field data from site records using the Rural Development Administration of Korea archives. Two common regional cropping systems, corn for Chun-Cheon and soybean for Jeon-Ju, and a conservation tillage system, such as contour-mulching plowing, were used in both sites in this study. Plant growth for corn and soybean crops was calibrated in a trial and error manner to obtain reasonable values when compared to observed values for canopy cover, plant height, residue cover, and crop yield. If measured data for initial conditions were not available, they were estimated with WEPP output from continuous simulation runs.

Climate Generator (CLIGEN) Parameters. CLIGEN (Nicks et al. 1995) is a stochastic weather generator that can produce climate input for WEPP and other natural resource models. CLIGEN predicts the occurrence of daily precipitation, related to precipitation frequency using a first-order, two-state Markov chain based on the transitional probability of a wet day following a wet day [(P(W | W)] and a wet day following a dry day [P(W | D)]. The daily precipitation amounts are generated using a skewed normal distribution, while the daily maximum and minimum temperatures are generated using normal distributions. In CLIGEN, daily weather is generated from monthly data, there is no dependency between months, and every variable is generated independently of other variables.

A number of different approaches have been used to generate climate sequences for assessing climate change impact on soil erosion (Yu 2005). Generally, mean monthly precipitation is the product of mean monthly wet day precipitation and the number of wet days in the month. The mean monthly wet day precipitation is one of the input parameters for CLIGEN, and the average number of wet days is related to the transition probabilities. Therefore, changes in precipitation amount can be affected through adjusting wet day precipitation, or transition probabilities, or both. In this study, we examined all three types of possible climate precipitation changes. CLIGEN (version 4.3) was used to generate 100-year climate sequences for a representative climate station in the study sites to predict runoff and soil loss with WEPP. Specifically, the three methods used here were (1) Adjust monthly mean daily precipitation depth on a wet day by –20%, –10%, 0%, +10%, and +20%; (2) Adjust the monthly transitional probabilities of daily rainfall occurrence by –20%, –10%, 0%, +10%, and +20%; and (3) Make both adjustments in 1 and 2 simultaneously. The adjustments to the CLIGEN input parameter files were made uniformly throughout the year (same adjustment made to each monthly parameter).

Results and Discussion

Observed Climate and CLIGEN Parameterization. Baseline climate was determined using measured daily precipitation, maximum temperature, and minimum temperature at the Chun-Cheon and Jeon-Ju weather stations between 1966 and 2005. Mean annual precipitation in Chun-Cheon and Jeon-Ju was 1,305 and 1,291 mm (50.9

and 50.4 in) from 1966 to 2005, respectively. The annual precipitation at Chun-Cheon was similar to Jeon-Ju except for a few years (figure 2).

The CLIGEN monthly precipitation parameters were derived from the measured daily data. The other parameters required were created for Chun-Cheon and Jeon-Ju from the CLIGEN database using a CLIGEN-support parameterization software program (USDA Agricultural Research Service and US Forest Service 2008). The total precipitation and wet day precipitation in Chun-Cheon was slightly greater than that in Jeon-Ju. However, the number of precipitation days in Jeon-Ju was much greater than that in Chun-Cheon (table 3). On a seasonal basis, the summer half of the year (April to September) accounted for 85.0% of the yearly precipitation in Chun-Cheon and 87.6% in Jeon-Ju. Also, wet day precipitation was 3.16 and 2.58 times higher in the summer months for Chun-Cheon and Jeon-Ju, respectively. However, the percentage of precipitation days in summer and winter were similar at both sites.

The change of precipitation in winter (October to March) on a monthly basis was uniform for both sites (figure 3), and the mean precipitation in Jeon-Ju was slightly higher than that in Chun-Cheon. However, the precipitation change in the summer months (April to September) was not uniform, and mean precipitation at Chun-Cheon was much higher than that in Jeon-Ju in July and August.

Figure 4 shows the change in the average precipitation on wet days between Chun-Cheon and Jeon-Ju for the study period, 1966 to 2005. The overall pattern is quite similar to that of monthly total precipitation for the sites (figure 3). In fact, the overall increase of summer precipitation in Chun-Cheon and Jeon-Ju can be attributed to an increase in precipitation amount on wet days and an increase in the number of wet days on average during the summer season. However, the average precipitation on wet days for the winter season in Jeon-Ju was a little more than that in Chun-Cheon. This indicates a higher soil loss potential for hillslopes in Jeon-Ju during the winter season.

Runoff and Soil Loss from Continuous WEPP Simulations. The WEPP model–predicted average annual mean values for surface runoff and soil loss in Chun-Cheon and Jeon-Ju are presented in table 4. CLIGEN-simulated mean precipitation depth in Chun-Cheon and Jeon-Ju were similar to the observed data (table 3) at about 1,300 mm y^{-1} (50.7 in yr^{-1}). Although the mean precipitation between the sites was similar, the model-predicted mean runoff in Jeon-Ju was 48.8% higher than that in Chun-Cheon, and mean soil loss in Chun-Cheon was 55.3% higher than that in Jeon-Ju.

Topography plays a key role in soil erosion estimates, as should be expected. Soil erosion predicted from the loess hills in Chun-Cheon was much higher than that in Jeon-Ju despite the lower surface runoff. The combination of topography and soil characteristics (table 1) strongly influenced the model runoff and soil loss predictions. The much steeper and more erodible sandy soils at Chun-Cheon had much greater predicted soil loss. Additionally, more soil loss from Chun-Cheon was also likely due to higher rainfall intensities there.

As a rough check on the WEPP model predicted values, the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) estimates of soil loss were also com-

Figure 2
Annual precipitation for Chun-Cheon and Jeon-Ju constructed from daily observations from 1966 to 2005.

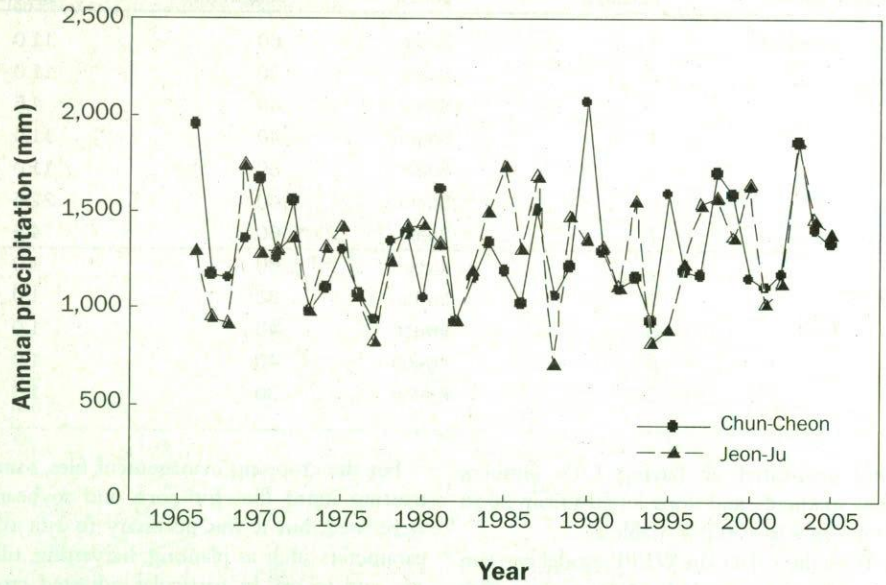


Table 3
Observed precipitation in Chun-Cheon and Jeon-Ju from 1966 to 2005.

	Chun-Cheon		Jeon-Ju	
Annual precipitation	(mm y^{-1})	(%)	(mm y^{-1})	(%)
Total	1,304.8	100.0	1,291.0	100.0
Summer (April to September)	1,109.5	85.0	1,131.3	87.6
Winter (October to March)	195.3	15.0	159.7	12.4
Wet day precipitation	(mm day^{-1})		(mm day^{-1})	
Annual average	10.6		9.9	
Summer (April to September)	16.1	3.16*	14.2	2.58*
Winter (October to March)	5.1		5.5	
Number of precipitation days	(days)	(%)	(days)	(%)
Annual average	96.9	100.0	120.0	100.0
Summer (April to September)	55.2	57.0	67.2	56.0
Winter (October to March)	41.7	43.0	52.8	44.0

* Ratio summer to winter.

Figure 3
Monthly mean precipitation in Chun-Cheon and Jeon-Ju between 1966 and 2005.

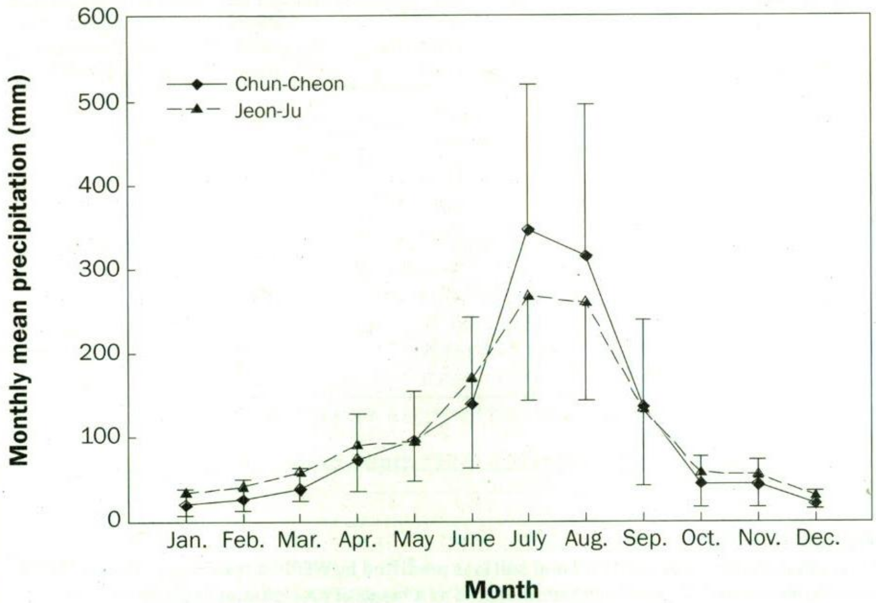


Figure 4
Mean wet day precipitation in Chun-Cheon and Jeon-Ju for 1966 to 2005.

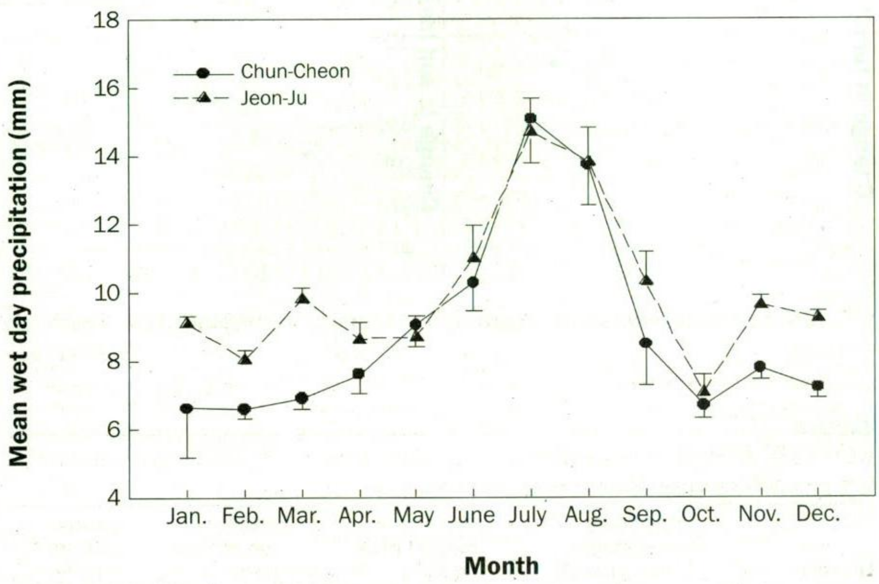


Table 4
WEPP model predicted 100-year average annual mean values for precipitation, surface runoff, and soil loss in Chun-Cheon and Jeon-Ju, Korea.

Location	Average annual precipitation (mm y^{-1})	Number of profiles (n)	Mean profile runoff (mm y^{-1})	Mean profile soil loss (t ha^{-1} y^{-1})
Chun-Cheon	1,276.1	7	198.2	19.8
Jeon-Ju	1,287.9	5	387.1	8.8

puted for each profile and averaged. Mean USLE soil loss values were 26.9 and 10.4 t ha^{-1} y^{-1} (10.9 and 4.2 tn ac^{-1} yr^{-1}) for the Chun-Cheon and Jeon-Ju profiles, respectively, which are of the same order of magnitude as those predicted by the WEPP model (19.8 and 8.8 t ha^{-1} y^{-1} [8.0 and 3.6 tn ac^{-1} yr^{-1}]). A constant C-factor was used in the USLE computations for both sites under conservation tillage row cropping, while with WEPP, plant growth, tillage operations, and other management specific to each crop and site were simulated through time. Most of the differences in soil loss between the two sites (whether with USLE or WEPP) were due to the major differences in slope gradients for the representative hillslope profiles at each site.

Impacts of Simulated Climate Changes. The precipitation, runoff, and soil loss changes estimated with WEPP as a result of changes in the frequency of precipitation events [modification of P(W | W) and P(W | D)] are presented in table 5 and figure 5. In general, average annual precipitation depth showed an approximate linear response to the transition probability changes (table 5). The predicted runoff response at Chun-Cheon also had a similar tendency as the precipitation response; however this was not the case at Jeon-Ju for the greatest increases in probability changes, with a 31% increase in predicted runoff for a 21% increase in mean annual precipitation. This greater runoff at Jeon-Ju did not result in greater than linear response soil loss (18% increase), while for Chun-Cheon, soil loss increased 18% and 26% with 12% and 23% increases in mean annual precipitation, respectively. Thus, for the steeper slopes at Chun-Cheon, a greater than linear response was seen for soil loss with increasing precipitation (and runoff), possibly due to greater contributions from nonlinear rill detachment processes. For both locations, model responses for decreases in precipitation showed fairly linear responses.

Table 6 and figure 6 provide the WEPP model results as affected by changing the mean depth of precipitation on a wet day. Runoff responses were linear and approximated the changes in predicted average annual precipitation depths (figure 6), as did predicted average annual soil loss at Chun-Cheon. However, erosion results for Jeon-Ju, while linear in response, had a definite bias of underprediction by about 50%. Changing the amount of precipitation on a wet day at

Jeon-Ju did not have as great an impact as increasing the frequency of wet days. This may be due to the low slope gradients at Jeon-Ju which favor interrill detachment and transport-limited erosion conditions, under which more frequent smaller events could produce more sediment loss than less frequent larger events.

Climate changes that involve both modification of the frequency of precipitation events and the depth of precipitation for those events showed the greatest impacts on predicted runoff and soil loss (table 7) (figure 7). For Chun-Cheon, 10% increases in the frequency and depth of precipitation resulted in a 33% increase in runoff and 30% increase in soil loss, while a 20% increase in the precipitation parameters caused 54% and 52% increases, respectively. Decreasing the climate change parameters at this site also had a large effect on decreasing the predicted runoff and soil loss, though not nearly as great a magnitude (range of 16% to 29% decreases) as with increasing severity. Simulation results for Jeon-Ju were quite similar for runoff predictions, but not for soil loss. A 20% increase in the combined climate generation parameters resulted in a 44% increase in predicted precipitation, 60% increase in predicted runoff, but only a 27% increase in predicted soil loss. Again, this may be due to a greater tendency towards interrill erosion and transport-limited erosion conditions on the low slope gradient profiles at Jeon-Ju, which decrease the tendency for increasing soil loss with major increases in predicted runoff. Overall these results indicate that changing climate may cause more severe problems at the Chun-Cheon location or other sites with similar conditions in Korea having more hilly terrain and sandy erodible soils.

The findings of this study were consistent with previous studies by Zhang et al. (2005, 2007) and others which revealed that precipitation increases are often positively correlated with erosion increases. This indicates that the change of precipitation, due to precipitation occurrence transition probabilities, mean wet day precipitation depth, and combinations of the two, can be realistic scenarios in representing the site-specific change of soil erosion. In future studies, additional effects of precipitation variance as well as temperature and CO_2 concentration will be investigated (Favis-Mortlock and Savabi 1996; Savabi and Stockdale 2001; Pruski and Nearing 2002b).

Table 5

WEPP model predicted 100-year average annual precipitation, runoff, and soil loss estimated with transition probability climate change scenarios.

Location	P(W|W) & P(W|D) change	Mean precipitation (mm y^{-1})	Mean runoff (mm y^{-1})	Mean soil loss (t ha^{-1} y^{-1})
Chun-Cheon	+20%	1,562.7	241.7	25.0
	+10%	1,424.9	206.3	23.4
	0	1,276.1	198.2	19.8
	−10%	1,159.1	180.2	17.4
	−20%	1,054.8	166.0	16.3
Jeon-Ju	+20%	1,562.7	507.9	10.4
	+10%	1,413.8	438.3	9.0
	0	1,287.9	387.1	8.8
	−10%	1,164.8	344.8	7.7
	−20%	1,053.8	308.2	7.3

Note: P(W|W) is the probability of a wet day following a wet day, and P(W|D) is the probability of a wet day following a dry day.

Figure 5

Changes in average annual runoff and soil loss predicted by WEPP in response to change in annual average predicted precipitation depths as a result of precipitation transition probability changes.

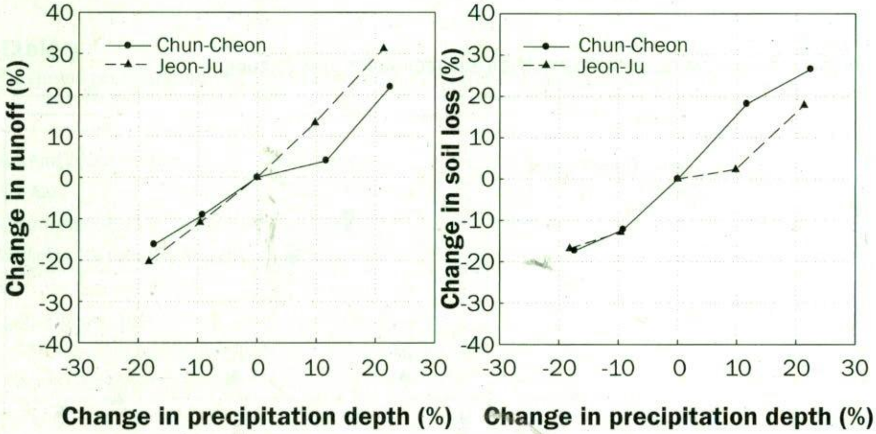


Table 6

WEPP model predicted 100-year average annual precipitation, runoff, and soil loss estimated with precipitation depth climate change scenarios.

Location	Mean daily precipitation depth change	Mean precipitation (mm y^{-1})	Mean runoff (mm y^{-1})	Mean soil loss (t ha^{-1} y^{-1})
Chun-Cheon	+20%	1,525.8	236.1	23.5
	+10%	1,395.2	216.1	21.5
	0	1,276.1	198.2	19.8
	−10%	1,171.7	183.4	18.2
	−20%	1,081.5	170.0	16.9
Jeon-Ju	+ 20%	1,530.2	472.0	9.7
	+10%	1,406.9	427.8	9.3
	0	1,287.9	387.1	8.8
	−10%	1,185.8	354.5	8.4
	−20%	1,089.1	324.8	8.0

Figure 6

Changes in average annual runoff and soil loss predicted by WEPP in response to change in annual average predicted precipitation depths as a result of mean wet day precipitation depth changes.

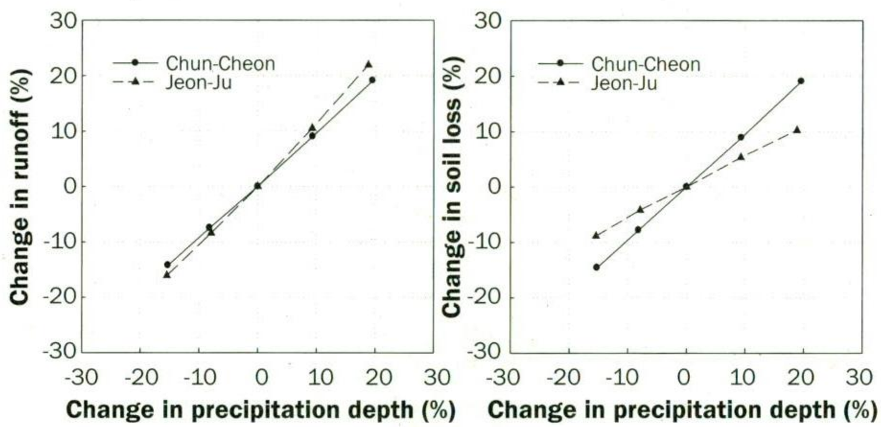


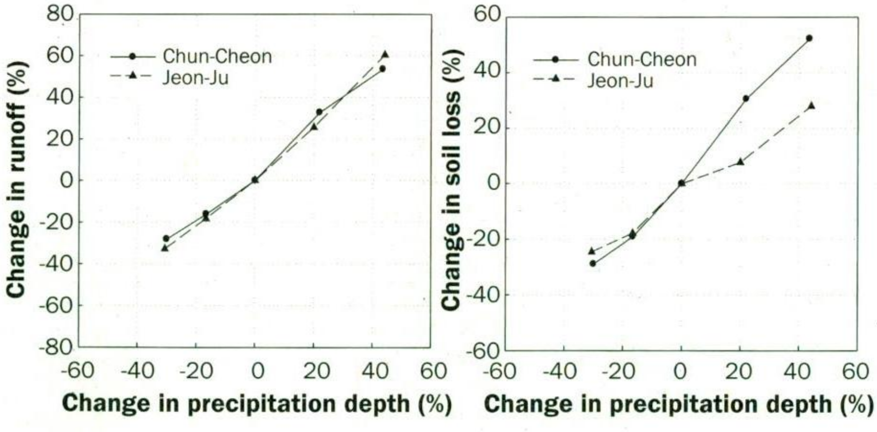
Table 7

WEPP model predicted 100-year average annual precipitation, runoff, and soil loss estimated with combined transition probability and precipitation depth climate change scenarios.

Location	Combined climate changes	Mean precipitation (mm y^{-1})	Mean runoff (mm y^{-1})	Mean soil loss (t ha^{-1} y^{-1})
Chun-Cheon	+20%	1,831.6	304.3	30.1
	+10%	1,556.1	262.8	25.8
	0	1,276.1	198.2	19.8
	−10%	1,064.3	166.2	16.0
	−20%	893.6	142.4	14.0
Jeon-Ju	+20%	1,856.1	620.6	11.2
	+10%	1,544.9	485.9	9.5
	0	1,287.9	387.1	8.8
	−10%	1,072.7	316.2	7.2
	−20%	893.5	260.3	6.6

Figure 7

Changes in average annual runoff and soil loss predicted by WEPP in response to change in annual average predicted precipitation depths as a result of combined transition probability and mean wet day precipitation depth changes.



Summary and Conclusions

This study was made possible with the application of WEPP and CLIGEN and the adjustment of CLIGEN precipitation parameters to generate realistic precipitation change scenarios for soil erosion and runoff prediction in Chun-Cheon and Jeon-Ju in Korea.

The precipitation records in Chun-Cheon and Jeon-Ju showed a similar trend with much higher values during June to August. Most of the increase in precipitation for the two sites is a result of the increase in wet day precipitation. The increase in the standard deviation of wet day precipitation was greater than that in the mean, implying greater precipitation variability during wetter periods.

In general, a number of different approaches have been used to generate climate sequences for assessing climate change impact on soil erosion. In this study, three precipitation-change scenarios were examined, changing the frequency of precipitation events, changing the depth of precipitation on a storm day, and changing both the frequency and amount of precipitation of wet days.

Topography plays a key role in soil erosion estimates, as should be expected. Soil erosion predicted for the loess hills in Chun-Cheon was much greater than that in Jeon-Ju despite lower predicted surface runoff. The combination of topography and soil characteristics strongly influenced this estimate as well as rainfall intensity.

The combination of increased frequency of precipitation events and increased depth of precipitation for an event resulted in the greatest increases in predicted runoff and soil loss, particularly for the hilly terrain and sandy soils at Chun-Cheon. Increasing frequency and depth by 20% in the climate generator inputs resulted in a 44% increase in predicted average annual precipitation, and 54% and 52% increases in predicted average annual runoff and soil loss, respectively. Impacts at the much flatter Jeon-Ju site were different, with a 44% increase in average annual precipitation resulting in a 60% increase in predicted runoff but only a 27% increase in predicted soil loss.

Many assumptions were required to assess soil loss and runoff under possible future climate change with WEPP in Korea. Additional testing with different crops, tillage systems, and crop rotations is recommended. However, the results here suggest a great potential for soil erosion increases in Korea, regardless of topography and soil characteristics, should projected increases in precipitation occur. More research needs to be done to identify new management practices to mitigate effects of possible climate change, especially on steep soil profiles.

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